

# Variational Data Assimilation in Shelf Circulation Models

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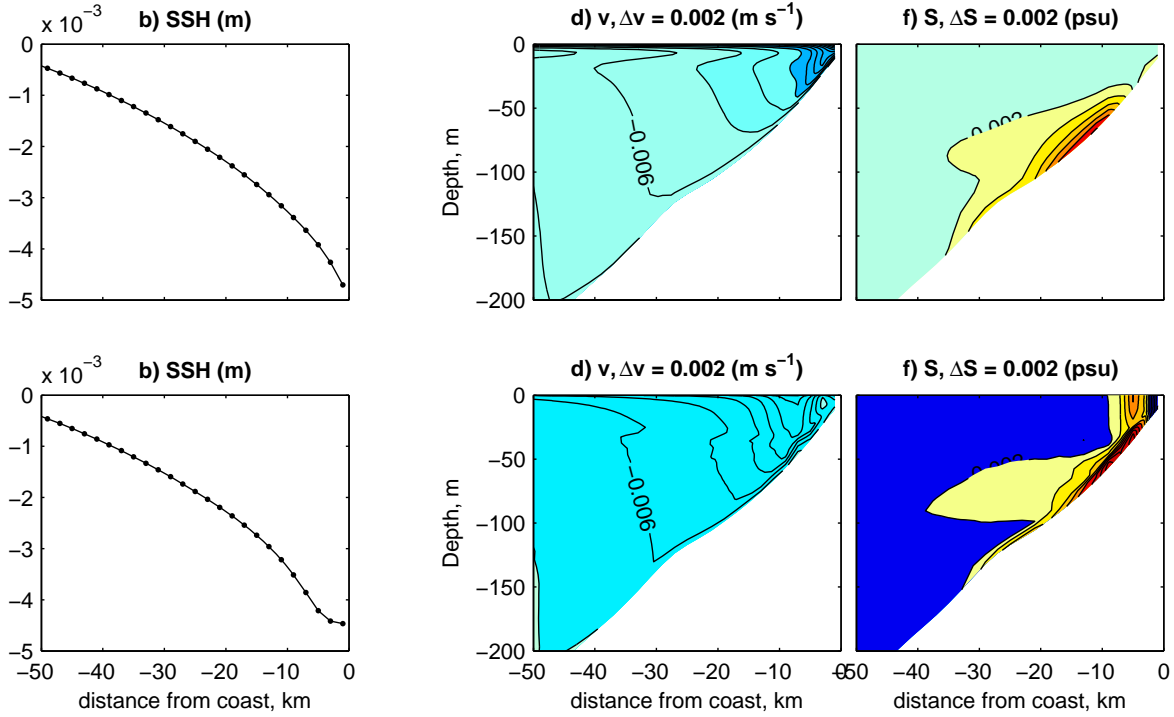
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## LONG-TERM GOALS

The goal of this research project is to develop advanced data assimilation (DA) methods for coastal circulation models and to test these methods with measurements from the Oregon shelf. We envision the development of an optimal, versatile, and relocatable DA system based on a primitive equation model with a turbulence submodel. The planned system could be used efficiently both for operational needs (forecasting, search and rescue, environmental response) and for fundamental studies of coastal ocean dynamics.

## OBJECTIVES

The immediate scientific objectives of this research project are to develop practical, but still nearly optimal methods for the assimilation of data into coastal circulation models, and to apply these methods to time-series measurements from moorings and coastally-based high frequency (HF) standard and long range radars, satellite data (SSH, SST), and hydrographic survey data (e.g., from autonomous underwater vehicles, AUVs, and gliders). An important additional scientific objective is to utilize data assimilation to study the physics of coastal ocean circulation processes, for instance, to understand the zones of influence of assimilated observations, covariability of processes over the shelf, in the coastal transition zone (CTZ), and in the adjacent interior ocean, to assess the impact of observational arrays, and to provide information on the magnitude and spatial and temporal structure of errors in model forcing.



*[Figure 1. Components of the multivariate representer solution (left to right: SSH, alongshore velocity, salinity), scaled by minus the expected model error in the observed quantity (of SSH at the distance of 20 km from coast), show the structure of the correction to the prior model due to assimilation of the single observation. This structure is consistent with the dynamics of upwelling since error decorrelation scale in the wind stress error is large (50 km) compared to the Rossby radius of deformation. The location of the zone of maximum influence of the observation depends on the background ocean conditions: (top) corresponding to the ocean at rest, and (bottom) corresponding to the upwelling background conditions (Kurapov et al., 2008)]*

## APPROACH

The proposed research involves a systematic continuation of work in progress that has included assimilation of current measurements from both moored instruments and an array of HF radars deployed along the Oregon coast. Additional data types, including satellite SST and SSH and in-situ sections of hydrographic and turbulence observations, have been used to verify the results of data assimilation. Studies of dynamics have been focused on wind-driven upwelling and internal tides on the shelf.

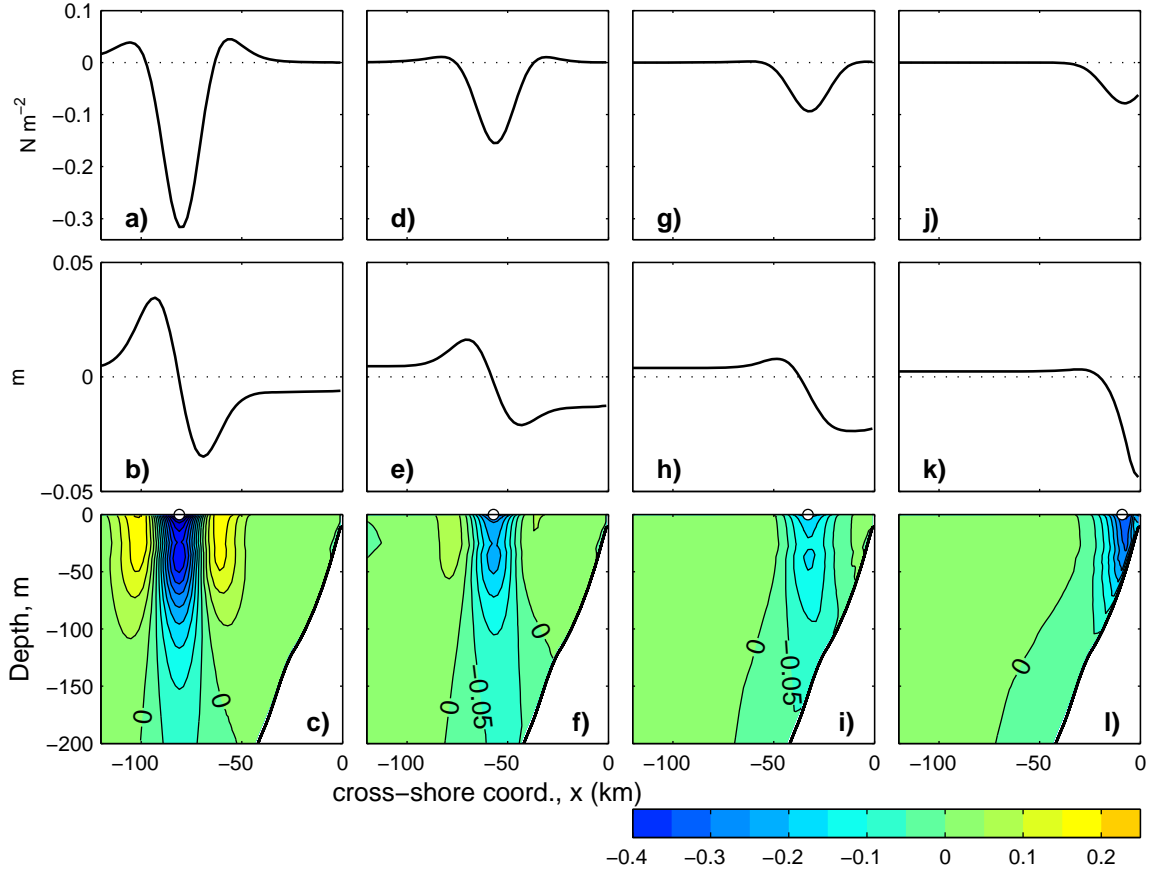
Initially, the problem of coastal data assimilation has been approached from two directions: (i) application of optimal, variational data assimilation schemes to simplified linear models (Scott et al. 2000, Kurapov et al. 1999, 2002, 2003) and (ii) application of simplified, sub-optimal data assimilation schemes [such as optimal interpolation (OI)] to a full primitive equation model (Oke et al. 2002, Kurapov et al. 2005a, 2005b, 2005c). In our implementation of the OI with the nonlinear, hydrostatic, primitive equation Princeton Ocean Model (Kurapov et al. 2005a, 2005b), state variables were updated sequentially based on data-model differences and stationary estimates of forecast and data error statistics. Such a simple sequential approach improves modeled coastal ocean circulation on average over the season. However, to improve prediction on the event scale, especially in intermittent regimes

(frontal meandering, coastal current separation, relaxation from upwelling to downwelling) more elaborate DA methods must be employed that rely on the time-dependent (ocean state dependent) forecast error statistics. So, more recently we have worked to merge the two abovementioned approaches, with focus on the development and implementation of the representer-based variational DA method (Chua and Bennett, 2001) with nonlinear high-resolution regional models of coastal ocean dynamics (Kurapov et al., 2007, 2008).

The representer-based method approaches the nonlinear optimization problem as a series of linearized optimization problems, each solved efficiently in the data subspace of the state space. This approach allows substantial flexibility in the choice of assumed error covariances. The resulting optimal solution can be viewed as an objective mapping of the assimilated observations utilizing covariances (mapping rules) that depend on the background nonlinear ocean state. The method is economical in that the model state error covariance (a very large matrix) is not computed explicitly. Utilizing the indirect representer algorithm (Egbert et al. 1994) as a linear solver, the method is applicable with large data sets. As for any variational method applied to a nonlinear dynamical model, the representer method requires repeated solution of the corresponding tangent linear (TL) and adjoint (ADJ) systems.

Instabilities and eddy interactions are common features in the highly energetic coastal ocean environment. Instability growth is constrained in a nonlinear model as a result of energy cascades. However, such a mechanism would not be necessarily present in the tangent linear model, and so exponential growth of instabilities may possibly pose a threat to convergence of an iterative optimization algorithm based on linearization. As a first step in addressing this issue, we have implemented the representer method for the shallow-water model of circulation in the nearshore surf zone (Kurapov et al. 2007). Currently, we are implementing a similar approach for a model of three-dimensional stratified flows. The nonlinear dynamics is based on the Regional Ocean Modeling System (ROMS, Haidvogel et al., 2000, Shchepetkin and McWilliams, 2005). We have tested the utility of the tangent linear and adjoint ROMS components (Moore et al. 2004, Di Lorenzo et al. 2007). Utilizing this experience, we have developed our own version of the tangent linear and adjoint codes, in which some of the deficiencies of the TL&ADJ ROMS have been resolved. This allowed us to facilitate progress with our project by completing a study of representers, array modes, and DA in a wind-driven coastal ocean (Kurapov et al., 2008).

Along with the development of DA methodology, we have continued to advance our 3D stratified model for the Oregon shelf flows, testing limited-area versions of ROMS with open boundary conditions suitable for the energetic coastal flows off Oregon (Springer et al., 2008) and studying possible interactions of wind- and tidally-driven baroclinic flows, three-dimensional Lagrangian transport in the eddy dominated CTZ, and the effects of submesoscale eddies on cross-shore transport. These efforts involved leverage of NOPP, GLOBEC, and NSF projects. Model improvements resulting from those tests will provide better physical compatibility between assimilated data and the model.

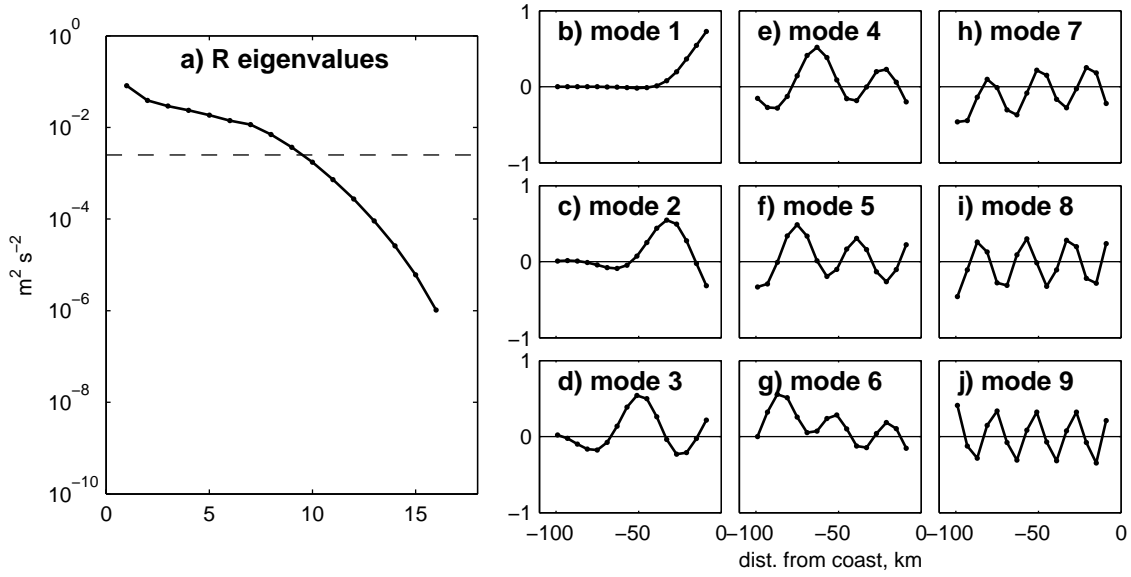


*[Figure 2: Representer components (top to bottom: wind stress, SSH, and alongshore velocity,  $v$ , in  $\text{m/s}$ ), scaled by minus the expected model error of the observation (surface  $v$  at a location shown as circle) show the structure of the model correction associated with surface Ekman pumping, since the assumed decorrelation scale in the wind stress error is small (10 km), compared to the Rossby radius of deformation. Representers for observations closer to the coast (columns of plots from left to right) are progressively more asymmetric with respect to the observation location (Kurapov et al., 2008).]*

## WORK COMPLETED

In the present project period, we have completed the following tasks: (1) The manuscript describing the implementation of the representer method with a nonlinear shallow water model of nearshore flows, focused on the eddy regimes, has been published (Kurapov et al. 2007). (2) Our version of the TL&ADJ codes that allowed progress in studies of coastal ocean DA has been completed to include all dominant terms. (3) These codes have been implemented together with nonlinear ROMS in a study of representers, array modes, and DA in a wind-driven coastal ocean, in an idealized alongshore uniform setting. A manuscript describing these experiences has been accepted for publication (Kurapov et al., 2008).

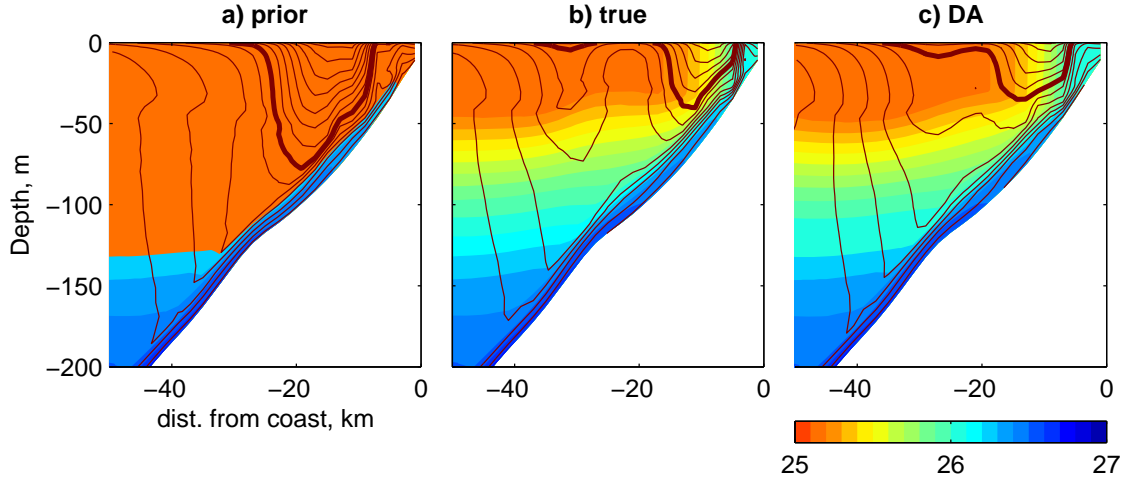
On the path to utilizing the representer method with a model of three-dimensional coastal circulation, we have tested our version of the TL and ADJ codes and resolved some of the



**[Figure 3: Array mode analysis, based on the eigenvalue decomposition of the representer matrix  $R$  (a matrix of prior model error covariances of observed quantities) provides a way to assess the potential impact of the array of observations, as shown here for the case of a cross-shore array of surface alongshore velocities (such as those from HF radars). (a) Eigenvalues of  $R$  are compared to the expected data error variance (dashed line) to show that 9 orthogonal linear combinations of representers have a larger model variance and so are better observed. (b)-(j) Singular vectors of  $R$  provide coefficients of those combinations, with relatively important observations near coast in the most stably observed modes (Kurapov et al., 2008)]**

deficiencies of the existing TL & ADJ ROMS codes. The concepts behind these algorithms have been shared with ROMS community via workshop presentations and publications (Kurapov et al., 2007, 2008), to possibly facilitate further advancement of ROMS community codes. In particular, one of the problems encountered with ROMS codes (Di Lorenzo et al., 2007) was that the impulsive (in time) forcing correction in the TL code excited large amplitude transients that dominated the low frequency balances such as geostrophy. We have developed, coded, and tested an adjoint algorithm that is strictly consistent with time-interpolation of the forcing in the nonlinear and tangent linear codes. Our modified code inhibits high frequency transients in the representer solutions when errors in the forcing are corrected. A similar algorithm can be applied to the dynamical errors on the r.h.s. of the model equations, which may be necessary in the future to provide a means for time-continuous control of baroclinic instabilities.

Another modification, included in our codes, allows assimilation of more general data types than is currently allowed in the standard ROMS. With this modification, any linear combination of data can be assimilated without further need to add to the tangent linear and adjoint codes. In particular, this facilitates assimilation of low-pass filtered data in a model representing both tidal and subtidal motions; demeaned alongtrack SSH; HF radar radial components; time- and area-average observations (e.g., SST composites).



**[Figure 4: Snapshots of nonlinear ROMS solutions in the DA twin experiment: (a) The prior model forced by the spatially and temporally uniform upwelling favorable wind stress ( $0.12 \text{ N/m}^2$ ); (b) The true solution forced by the wind stress reduced inshore of the upwelling front by the factor of 2; (c) The solution forced by the wind stress corrected by assimilation of surface  $v$  observations. Contour lines are southward velocity every  $0.1 \text{ m/s}$ , with bold contour corresponding to  $0.5 \text{ m/s}$ . Colored contours are the potential density (Kurapov et al. 2008).]**

Our TL&ADJ model has been tested in an idealized, alongshore uniform, coastal setting, as described in Kurapov et al. (2008). In particular, representers have been analyzed to verify dynamical consistency in the correction fields. Uncertainty was assumed in the alongshore wind stress. We have studied the dependency of representers (which provide information on the prior model error covariance) on the state of the ocean (upwelling or neutral conditions), bathymetry, observation type (SSH or surface velocity), and the assumptions of the forcing decorrelation length scale. In a similar configuration, the impact of the cross-shore arrays of SSH and surface velocity observations has been analyzed by computing the orthogonal array modes (Bennett, 2002). A DA test with synthetic observations of surface velocity has been performed to demonstrate that variational DA is capable of correcting the model error associated with variability in the wind stress inshore of the upwelling front, similar to that caused by effects of atmosphere-ocean interaction (Perlin et al., 2007).

Presently, representer analyses are continued in three dimensions and time, with focus on the alongshore propagation of measured information by coastally trapped waves and advection by the coastal jet. The assimilation experiment is being prepared to assimilate alongtrack SSH altimetry and HF radar measurements in the area of Cape Blanco where instabilities and eddies limit predictability of the prior model.

## RESULTS

Our results with the shelf circulation model (Kurapov et al., 2008) have demonstrated that the prior model error covariance is sensitive to the background ocean conditions. For instance (Figure 1), as seen in the cross-shore section of the representer (which is an error covariance between the observed quantity and all the elements of the model state space), an observation of SSH has the maximum influence near the coast when the ocean is at rest. In the presence of the upwelling jet, the same observation has the maximum influence in the core of the jet. The representer has a different spatial

structure depending on the cross-shore decorrelation scale in the wind stress. For instance, examples in Figure 1 were obtained for the case of a large decorrelation scale (50 km) and the multivariate representer shows co-variability in model errors consistent with the structure of classical upwelling. In contrast, representer computed with small decorrelation scale in the wind stress (10 km), exhibit the structure more consistent with Ekman pumping. Also, Figure 2 shows the asymmetry in the spatial structure of the representer for shelf observations, compared to the relatively symmetric structure found for observations in the interior ocean.

Array mode analysis (Figure 3) for a cross-shore array of surface alongshore velocity measurements has suggested that such an array would be useful to correct model errors associated with errors in the wind stress of a relatively small spatial scale (10 km). The dominant, most stably observed, modes place a larger weight on shelf observations. Additional analyses have shown that the array of SSH observations over the shelf will not be as effective in correcting model error of the same nature.

The DA test with synthetic observations (Figure 4) has demonstrated that our DA system can be effective correcting the wind stress error and associated inconsistency in the baroclinic coastal jet structure.

## **IMPACT/APPLICATIONS**

Representer analyses using our modified version of the tangent linear and adjoint ROMS codes have provided information on the zones of influence of the surface observations, such as SSH altimetry and HF radar surface velocities. Array mode analyses and DA tests have shown the potential of HF radar observations correcting the model error associated with wind stress uncertainty.

## **TRANSITIONS**

Our latest advances in modeling the Oregon shelf flows have been incorporated into a pilot real-time forecast model (supported by NOAA) that has produced daily updates of three-day ocean forecasts. The forecast graphics have been posted online at <http://www-hce.coas.oregonstate.edu/~orcoss/NCTZ/SSCforecast.html>, as well as on the pages of the Oregon Coastal Ocean Observing System (OrCOOS) ([www.orcoos.org](http://www.orcoos.org)). These forecasts provided guidance to the OSU glider group (Barth, Shearman) in their daily operations and to Dr. M. Levine during the dye release experiment in summer 2008. Local fishermen have found SST forecasts useful to track tuna.

## **RELATED PROJECTS**

Progress on variational data assimilation through this project will directly benefit the research in two projects: (1) “Effects of meso- and basin scale variability on zooplankton populations in the California Current System using data-assimilative, physical/ecosystem models”, US-GLOBEC-NEP, NOAA and (2) “Boundary conditions, data assimilation, and predictability in coastal ocean models”, ONR-NOPP.

A Ph.D. student John Osborne began working with us last fall supported by the NSF grant on “Modeling and Assimilation of Internal Tides in Interaction with Subinertial Wind-Forced Flows in the Coastal Ocean” (PI: Kurapov, co-PI: Egbert). On this project, we are building and analyzing the outputs of the Oregon shelf model at a high resolution (<1 km in horizontal), including tidal forcing. This

model will be nested in our 3-km data assimilative product. Our tangent linear and adjoint codes will be utilized to assimilate long-range HF radar data in the tidal frequency band.

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## **PUBLICATIONS**

Kurapov, A. L., G. D. Egbert, J. S. Allen, and R. N. Miller, 2007: Representer-based variational data assimilation in a nonlinear model of nearshore circulation, *J. Geophys. Res.*, 112, C11019, doi:10.1029/2007JC004117. [PUBLISHED, REFEREED]

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